NEW TECHNOLOGIES AND EQUIPMENT

UDC 666.1.038.2:621.365.46.004.14

IR-ANNEALING TECHNOLOGY FOR GLASS PRODUCTS

V. E. Tyutyunnik[1] and Yu. A. Guloyan[1]

Translated from Steklo i Keramika, No. 8, pp. 33 – 36, August, 2000.

The advantages of IR annealing of glass and glass products, as compared with convective annealing, are demonstrated. Results of testing of IR annealing of glass products are described.

Mass production of glass articles is usually carried out in furnaces with convective heat transfer. Due to the poor thermal conductivity of glass, a high-quality annealing process requires a rather long time. In using penetrating infrared radiation, the temperature across the glass article walls soon equalizes, and the heating and cooling processes are significantly accelerated [1 – 4].

An analysis of the above-mentioned publications and the data of studying radiative-conductive heat exchange (RCH) in the cooling of glasses [5 – 7] made it possible to expand the theoretical principles of intense radiation annealing, demonstrate certain new possibilities of this method, and implement this method in practice in a new annealing furnace for industrial production.

The use of radiation heating called for the development of an original method for theoretical evaluation of the temperature state of glass products positioned on the conveyer belt inside a rectangular tunnel chamber. The method is based on mathematical models of RCH, numerical methods, and algorithms and is implemented as a series of software programs for IBM PC/AT computers [8]. The method makes it possible to study the temperature state of articles under the effect of such factors as nonstationary and spatially inhomogeneous descending radiation flows, natural or forced convection, the temperature dependence of the thermophysical and optical properties of the glass, and volume absorption of radiation by the glass.

This method was used to study the cooling parameters of glass products and show the possibility for multiple acceleration of this process, using the factor of volumetric equalizing of the temperature field of a glass article, employing an external radiator. The results obtained were verified in an experimental annealing furnace for hollow products.

An experimental device developed for determining the RCH parameters was also used in the investigation.

[1] Research and Development Institute of Glass, Moscow, Russia.

The temperature region of formation of residual stresses in glass is determined by the region of transition from the unstable softened state to the solid vitreous state. This region can be called the critical annealing region, and we analyzed precisely this region, using the cooling of a glass plate as an example.

The theoretical-experimental model of a glass article is represented as a glass plate bounded by a system of reflectors. IR heaters are installed between the plate and the reflectors, and these heaters have a constant spiral color temperature of 2600 K during the entire process.

The glass layer is separated from the nontransparent metal surfaces by diathermal air clearances. The reflection at the glass – air and air – metal interfaces is a mirror reflection, and the corresponding reflective (or radiating) capabilities are calculated based on the Fresnel formulas. To calculate radiation flows in the “furnace roof – glass layer” system, the assumption is made that the whole surface is the source of a uniform radiation flow.

The solution of the RCH problem under these conditions is based on the use of difference schemes. The nonlinear problem related to the temperature dependence of the optical and thermophysical properties of the material and the presence of an inherent thermal flow (both volumetric and surface) caused the need for an iterative solution for each time step. In solving the problem of spectral radiation transfer, the multigroup approximation is used, i.e., the region of partial transparency is split into groups in which the optical properties do not depend on the wavelength.

The calculation of RCH for a glass article was performed for a variable descending radiation flow with different heat transfer coefficients. The thermophysical properties were taken from the database of the Research and Development Institute of Glass, which is partly published in [5, 9, 10] (RF Patent No. 2078063).

Results of numerical modeling of the radiative-cooling process in the annealing of the bottom part of an article (a

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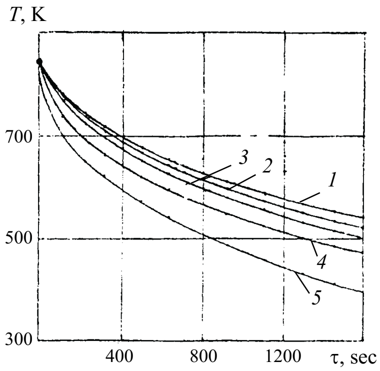

Fig. 1. Temperature variation kinetics in annealing the bottom part of an article (a tumbler): *1*, *2*, *3*, *4*, and *5*) heat transfer coefficients 0, 5, 10, 20, and 50 W/(m^2 · K), respectively.

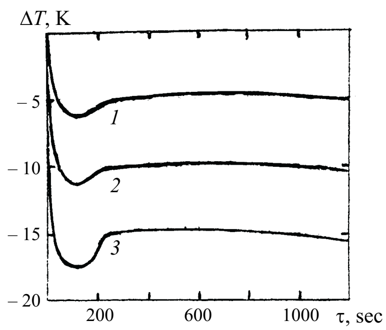

Fig. 2. Variation in the temperature difference in glass (1 cm thick) in time: *1*, *2*, and *3*) heat flow density 10^4, 5×10^4, and 10^5, respectively.

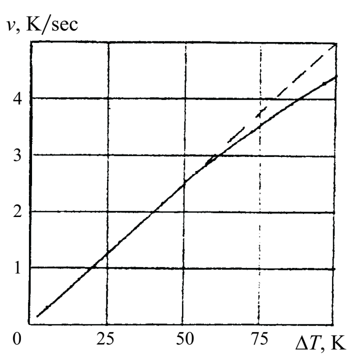

Fig. 3. Dependence of the glass cooling rate on the temperature difference at the boundaries of a layer 1 cm thick.

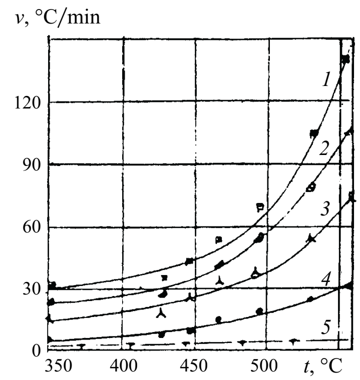

Fig. 4. Temperature dependence of the rate of IR annealing of a glass plate 1 cm thick: *1*, *2*, *3*, *4*, and *5*) stresses 75, 50, 25, 0, and 50 nm/cm (convective annealing), respectively.

tumbler) are given in Fig. 1. The natural convection as well has a certain effect on the increase in the rate of annealing: for the heat transfer coefficient 20 W/(m^2 · K), the annealing rate is 0.9 K/sec, and in the absence of convection, this rate is 0.4 K/sec. Under the conditions considered, the annealing rate reached such values that even in the case of insignificant convection (Fig. 1, curve *2*) the critical-annealing phase proceeded for 5 min.

The temperature difference varying in time for various values of the heat flow density (Fig. 2) indicates that the heat transfer process becomes monotonic 200 sec after the beginning of cooling, which makes it possible to apply the regularities of monotonic cooling in RCH to this phase of the annealing process (starting with T_g) and thus to interpret the effect of various factors on the cooling rate.

For instance, according to the data in [6], the increment ΔT leads to a nonlinear dependence of the cooling rate only for sufficiency large values of ΔT (Fig. 3).

Based on the obtained experimental and theoretical results, calculations of the properties and parameters of RCH were carried out, which indicated that radiative transfer of energy from external sources is significantly larger than the true thermal conductivity of glass. This factor determines to a large extent the small temperature differences in a layer 1 cm thick at high cooling rates and, accordingly, the low residual stresses.

Figure 4 represents the temperature dependence of the IR annealing rate for constant preset stresses. As can be seen, the rates of IR annealing significantly exceed the rates of convective annealing. For a stress of 2 MPa and a temperature of 350°C, the rate ratio is 10, and for 550°C and the same stress, the ratio is 21.

The calculated and experimental data show that it is possible to obtain zero stresses in radiative annealing, due to the intense heat exchange between the layers and the volumetric equalizing of temperature across the cooling-glass thickness. This opens possibilities for substantial intensification of annealing, especially for critical products, for example, optical glass.

Compared to the new radiative annealing method, the one described in [2] can be called the radiative-convective method, since in addition to radiative removal of energy from the glass, an external convective energy flow is deliberately directed upon the glass surface for the purpose of decreasing the temperature difference inside the glass layer, and in this manner it compensates the radiative-convective flow from the surface.

The new method, which involves not only volume cooling, but a volumetric decrease in the value of the temperature

difference inside the glass as well under the effect of an external heat radiation flow, should be called "purely radiative annealing." The advantage of the new annealing method, compared to the convective-radiative method, consists in a significant increase in the rate of annealing. Furthermore, the external radiative flow emitted by the articles in the new method is nearly half the corresponding convective flow, in order to minimize the temperature differences inside the glass. This can be clearly seen in Fig. 5 and is evidence of the better energy saving under the new method, as compared with the convective-radiative technology. In the new method, the external-radiation flow directed to the annealing-chamber walls is reflected and returned to the extent of 85 – 90%, whereas the convective air flow arriving at the water coolers is to a large extent absorbed by the water.

In the new method with multiple reflection from the reflectors, only 10 – 15% of the descending flow is absorbed by the cooling water. The radiative coolers in the method described in [2] absorb 80 – 90% of the convective heat flow, the difference between the water and air temperatures being equal to 850°C.

The ratio between the energy flows descending on the glass is of interest in the context of reducing the temperature differences for the methods considered [2, 8]. The ratio between the radiative flow emitted by external sources and the convective flow amounts to 0.15 for the maximum temperature of annealing and to 0.22 for the minimum annealing temperature. This indicates the energy advantage of the new annealing method.

Thus, the use of penetrating IR radiation ensures rapid equalizing of temperatures over the cross section of the glass product wall, significantly accelerates the heating and cooling rates, and improves the quality of annealing.

The intensification of the heat exchange due to the radiative component makes it possible to increase multiply the rate of high-quality annealing. We have developed successful technological and design solutions for effective zones of radiation, which makes it possible to ensure high efficiency of the process and, at the same time, significantly reduce energy and metal consumption and decrease the annealing-furnace size.

The data obtained were used to develop a new annealing furnace that was tested at Sitall JSC for annealing clear glass bottles. The aim was to obtain residual stresses of 20 – 50 nm/cm in all products. Tests showed good quality of annealing and good results in specific fuel consumption, which was significantly reduced, compared to the energy consumption in the PKÉ-323 furnace currently used at the factory. Figure 6 presents the time dependence of the temperature in the course of annealing in the PKÉ-323 convective furnace, a furnace made by CNUD, and the furnace with IR radiation. The data for the furnace with IR radiation and the PKÉ-323 furnace were obtained from portable bottom thermocouples, and the data from the CNUD Company were taken from [11]. It can be seen that the furnace with IR radiation provides a significant reduction in the annealing duration, due to rapid and uniform heating and cooling of the product walls. Consequently, products require a shorter exposure at the maximum temperature of annealing.

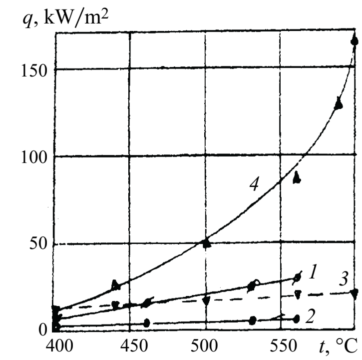

Fig. 5. Temperature dependence of the heat flow density in annealing glass plates 1 cm thick for various annealing methods: *1*) radiation flow from an external source: the method described in [8]; *2*) absorption of part of the external radiation flow by water-cooled reflectors: the method described in [8]; *3*) convective flow partially compensated by glass surface radiation: method of [2]; *4*) convective flow absorbed by coolers: method of [2].

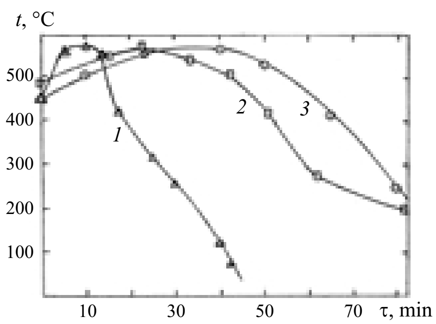

Fig. 6. Time dependence of the temperature in annealing bottles made of clear glass (bottom thickness 0.6 cm): *1*) furnace with IR radiation; *2*) electric furnace made by CNUD; *3*) PKÉ-323 electric furnace.

Based on the test results, some additional improvements were introduced into the technology, the most important of which were conversion to air cooling of the reflectors and solution of the problem of accelerated and safe cooling of the products after their exposure at the maximum annealing temperature.

The process of annealing of complex-shaped articles made of lead crystal (handwork) was tested at the Zolotkovo Glass Works.

Comparative industrial tests of the rate of annealing were performed in the convective furnaces and in the Utro-700 furnace with IR radiation, employing portable bottom thermocouples. The annealing rate was evaluated from the temperature variation kinetics within the annealing temperature range and the time of the end of annealing. The tests were performed at a constant efficiency of 420 kg/h and a residual stress of 45 nm/cm.

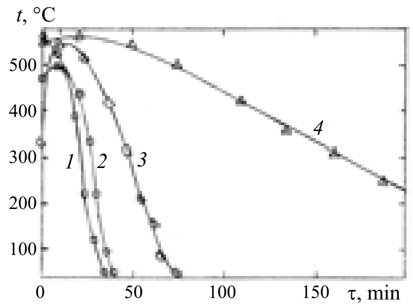

Fig. 7. Time dependence of the temperature in annealing products made of KhS-18 lead crystal: *1*) furnace with IR radiation (product wall thickness 0.5 cm, grid movement speed 0.46 m/min); *2*) furnace with IR radiation (product wall thickness 3.5 cm, grid movement speed 0.38 m/min); *3*) PKÉ-323 furnace (product wall thickness 0.5 cm, grid movement speed 0.26 m/min); *4*) PKÉ-323 furnace (product wall thickness 3.5 cm, grid movement speed 0.06 m/min).

The test results are shown in Fig. 7. It can be seen that annealing in the furnace with IR radiation is substantially accelerated, as compared with the convective furnaces. The difference in the annealing duration is especially significant for thick-walled products. The grid movement speed inside the furnace with IR radiation is close for annealing products having different wall thickness (0.46 and 0.38 m/min), whereas in the convective furnaces, the difference in speed is significant (0.26 and 0.06 m/min). This indicates that articles with different wall thickness can be annealed in the same IR radiation furnace at a constant rate (0.38 m/min), whereas when products of different thickness are annealed in a convective furnace, the process has to proceed at a significantly lower speed (0.06 m/min). Obviously, the specific energy consumption is substantially reduced by using the furnace with IR radiation.

The data obtained fully corroborate the results of laboratory test and studies. The Utro-700 furnace with IR radiation can easily replace two PKÉ-323 convective-annealing furnaces.

Technical specifications of the Utro-700 furnace with IR radiation

Efficiency, kg/h . . . . 420 – 620
Products made of KhS-18
lead crystal . . . . Flower vases, fruit vases, jugs, baskets, wine glasses, tumblers, etc.
Product dimensions, mm:
height . . . . 65 – 300
diameter . . . . 51 – 200
difference in thickness . . . . 5 – 35
Annealing temperature, °C:
maximum 510
minimum 330
Annealing interval duration, min . . . . 20.3 – 47.5

The results of a comparative study of a convective furnace and a furnace with IR radiation at the Zolotkovo Works are given in Table 1. The data on the annealing rate and the energy consumption relate to the recorded residual-stress values in the glass articles (45 nm/cm).

TABLE 1

Parameter	"Utro-700" furnace	PKÉ-323 furnace
Annealing rate in temperature range 510 – 330°C, K/min	24.55	1.88
Energy consumption rate, kW/h	55.0	176.5
Cross-sectional area of furnace working space (width × height), m^2	3.73	8.80
Furnace dimensions (length × width × height), m	17.7 × 1.1 × 1.8	21.70 × 2.56 × 2.48

The results of the testing of the IR annealing furnace and the specified technology, which lasted for several months, demonstrated the reliability of the method and the possibility of its successful application for annealing of household glass, bottles, sheet glass, and other products.

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